CLAIMS

What is claimed is:

1.   A radio frequency integrated circuit (RFIC) comprises:

5   transmitter section operably coupled to convert outbound baseband signals into outbound radio frequency (RF) signals;

receiver section operably coupled to convert inbound RF signals into inbound baseband signals, wherein the receiver section includes:

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a low noise amplifier operably coupled to amplify the inbound RF signals to produce amplified inbound RF signals;

down-conversion module operably coupled to convert the amplified inbound RF

15   signals into baseband in-phase components and quadrature components;

orthogonal-normalizing module operably coupled to:

obtain a first coefficient that is based on at least one of power of the

20   baseband in-phase components, power of the baseband quadrature components, and cross-correlation between the baseband in-phase components and the baseband quadrature components;

obtain a second coefficient that is based on at least one of the power of the

25   baseband in-phase components, the power of the baseband quadrature components, and the cross-correlation between the baseband in-phase components and the baseband quadrature components;

normalize an orthogonal relationship between the baseband in-phase

30   components and the baseband quadrature components based on the first

coefficient and the second coefficient to produce normalized in-phase components and normalized quadrature components; and

5   baseband processor operably coupled to recapture data from the normalized in-phase and quadrature components.

2.   The RFIC of claim 1, wherein the orthogonal-normalizing module comprises:

a first multiplier module operably coupled to multiple the baseband in-phase components

10   with the first coefficient to produce the normalized in-phase components;

a second multiplier module operably coupled to multiple the baseband in-phase components with the second coefficient to produce the cross-correlation; and

15   a subtraction module operably coupled to subtract the cross-correlation from the baseband quadrature components to produce the normalized quadrature components.

3.   The RFIC of claim 2, wherein the first multiplier module comprises:

20   a first plurality of shift registers operably coupled to produce a plurality of shifted representations of the baseband in-phase components;

switch matrix operably coupled to pass selected ones of the plurality of shifted representations of the baseband in-phase components and the baseband in-phase

25   components based on the first coefficient; and

an adder operably coupled to add the selected ones of the plurality of shifted representations of the baseband in-phase components and the baseband in-phase components to produce the normalized in-phase components.

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4.   The RFIC of claim 2, wherein the second multiplier module comprises:

a first plurality of shift registers operably coupled to produce a plurality of shifted representations of the baseband in-phase components;

5   switch matrix operably coupled to pass selected ones of the plurality of shifted representations of the baseband in-phase components based on the second coefficient; and

an adder operably coupled to add the selected ones of the plurality of shifted

10   representations of the baseband in-phase components to produce the cross-correlation.

5.   The RFIC of claim 1, wherein the orthogonal-normalizing module comprises:

a first multiplier module operably coupled to multiply the baseband in-phase components

15   with the second coefficient to produce the cross-correlation;

a subtraction module operably coupled to subtract the cross-correlation from the baseband quadrature components to produce phase adjusted quadrature components; and

20   a second multiplier module operably coupled to multiply the phase adjusted quadrature components with the first coefficient to produce the normalized quadrature components, wherein the baseband in-phase components are passed as the normalized in-phase components.

25   6.   The RFIC of claim 1, wherein the orthogonal-normalizing module comprises:

a first programmable register for storing the first coefficient; and

a second programmable register for storing the second coefficient, wherein the first and

30   second coefficients are determined by a trail and error manufacturing test.

7.   The RFIC of claim 1, wherein the orthogonal-normalizing module comprises:

a full matrix multiply module operably coupled to multiply the baseband in-phase components and the baseband quadrature components with a coefficient matrix that includes the first and second coefficients to produce the normalized in-phase components and the normalized quadrature components.

8.   The RFIC of claim 1, wherein the orthogonal-normalizing module further functions to:

measure local oscillation leakage power to produce a first power measurement;

provide a first magnitude signal to an in-phase portion of the receiver section and a zero magnitude signal to a quadrature portion of the receiver section;

measure power of the in-phase portion and power of the quadrature portion while processing the first magnitude signal and the zero magnitude signal, respectively, to produce a second power measurement;

provide the first magnitude signal to the quadrature portion of the receiver section and the zero magnitude signal to the in-phase portion of the receiver section;

measure the power of the in-phase portion and the power of the quadrature portion while processing the zero magnitude signal and the first magnitude signal, respectively, to produce a third power measurement;

determine a gain imbalance based on the first, second, and third power measurements;

provide a second magnitude signal to the in-phase portion and to the quadrature portion;

measure the power of the in-phase and quadrature portions while processing the second magnitude signal to produce a fourth power measurement;

provide the second magnitude signal to the in-phase portion and a negative second

5   magnitude signal to the quadrature portion;

measure the power of the in-phase portion and the power of the quadrature portion while processing the second magnitude signal and the negative second magnitude signal, respectively, to produce a fifth power measurement; and

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determine a phase imbalance based on the first, fourth, and fifth power measurements, wherein the gain imbalance and the phase imbalance correspond to the power of the baseband in-phase components, the power of the baseband quadrature components, and the cross-correlation between the baseband in-phase components and the baseband

15   quadrature components to determine the first and second coefficients.

9.   The RFIC of claim 1, wherein the orthogonal-normalizing module further functions to obtain the first and second coefficients by:

20   measuring in-phase signal level of the receiver section while processing a sine wave;

measuring quadrature signal level of the receiver section while processing the sine wave;

determining the power of the baseband in-phase components based on the in-phase signal

25   level;

determining the power of the baseband quadrature components based on the quadrature signal level;

30   determining cross-correlation power based on the in-phase signal level and the quadrature signal level; and

determining the first and second coefficients based on the power of the baseband in-phase components, the of the baseband quadrature components, and the cross-correlation power.

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10.   The RFIC of claim 1, wherein the orthogonal-normalizing module normalizes the orthogonal relationship between the baseband in-phase components and the baseband quadrature components by:

10   selecting one of the baseband in-phase components and the baseband quadrature components as a reference component; and

normalizing another one of the baseband in-phase components and the baseband quadrature components to the reference component.

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11.   The RFIC of claim 1, wherein the orthogonal-normalizing module further functions to:

update the first and second coefficients to compensate for at least one of temperature
20   variation and aging.

12.   A radio frequency integrated circuit (RFIC) comprises:

transmitter section operably coupled to convert outbound baseband signals into outbound radio frequency (RF) signals;

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receiver section operably coupled to convert inbound RF signals into inbound data, wherein the receiver section includes:

a low noise amplifier operably coupled to amplify the inbound RF signals to
10   produce amplified inbound RF signals;

down-conversion module operably coupled to convert the amplified inbound RF signals into baseband in-phase components and quadrature components;

15   orthogonal-normalizing module including:

an in-phase power module operably coupled to determine power of the baseband in-phase components;

20   a quadrature power module operably coupled to determine power of the quadrature components;

a cross-correlation power module operably coupled to determine a cross-correlation power based on the baseband in-phase and quadrature
25   components; and

normalizing module operably coupled to normalize the baseband in-phase components and the baseband quadrature components based on the power of the baseband in-phase components, the power of the baseband
30   quadrature components, and the cross-correlation power to produce

normalized in-phase components and normalized quadrature components; and

baseband processor operably coupled to recapture the inbound data from the normalized in-phase and quadrature components.

13. The RFIC of claim 12, wherein the normalizing module comprises:

a coefficient module operably coupled to determine coefficients based on the power of the baseband in-phase components, the power of the baseband quadrature components, and the cross-correlation power, wherein the baseband in-phase components and the baseband quadrature components are normalized based on the coefficients.

14. The RFIC of claim 12, wherein the in-phase power module comprises:

a multiplier operably coupled to square the baseband in-phase components to produce squared in-phase values; and

an accumulator operably coupled to accumulate the squared in-phase values for a predetermined period of time to produce the power of the baseband in-phase components.

15. The RFIC of claim 12, wherein the quadrature power module comprises:

a multiplier operably coupled to square the baseband quadrature components to produce squared quadrature values; and

an accumulator operably coupled to accumulate the squared quadrature values for a predetermined period of time to produce the power of the baseband quadrature components.

16. The RFIC of claim 12, wherein the cross-correlation power module comprises:

a multiplier operably coupled to multiply the baseband in-phase components and the baseband quadrature components to produce cross-correlation values; and

5   an accumulator operably coupled to accumulate the cross-correlation values for a predetermined period of time to produce the cross-correlation power.

17.   A radio frequency integrated circuit (RFIC) comprises:

receiver section operably coupled to convert inbound radio frequency (RF) signals into inbound baseband signals;

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transmitter section operably coupled to convert outbound data into outbound RF signals, wherein the transmitter section includes:

baseband processor operably coupled to convert the outbound data into the baseband in-phase components and baseband quadrature components;

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orthogonal-normalizing module operably coupled to:

obtain a first coefficient that is based on at least one of a gain imbalance and phase imbalance;

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obtain a second coefficient that is based on at least one of the gain imbalance and the phase imbalance;

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normalize an orthogonal relationship between the baseband in-phase components and the baseband quadrature components based on the first coefficient and the second coefficient to produce normalized in-phase components and normalized quadrature components;

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up-conversion module operably coupled to convert the normalized in-phase components and normalized quadrature components into RF signals; and

power amplifier operably coupled to amplify the RF signals to produce the outbound RF signals.

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18.   The RFIC of claim 17, wherein the orthogonal-normalizing module comprises:

a first multiplier module operably coupled to multiple the baseband in-phase components with the first coefficient to produce the normalized in-phase components;

5   a second multiplier module operably coupled to multiple the baseband in-phase components with the second coefficient to produce cross coupled in-phase components; and

a subtraction module operably coupled to subtract the cross coupled in-phase components 10   from the baseband quadrature components to produce the normalized quadrature components.

19.   The RFIC of claim 18, wherein the first multiplier module comprises:

15   a first plurality of shift registers operably coupled to produce a plurality of shifted representations of the baseband in-phase components;

switch matrix operably coupled to pass selected ones of the plurality of shifted representations of the baseband in-phase components and the baseband in-phase 20   components based on the first coefficient; and

an adder operably coupled to add the selected ones of the plurality of shifted representations of the baseband in-phase components and the baseband in-phase components to produce the normalized in-phase components.

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20.   The RFIC of claim 18, wherein the second multiplier module comprises:

a first plurality of shift registers operably coupled to produce a plurality of shifted representations of the baseband in-phase components;

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switch matrix operably coupled to pass selected ones of the plurality of shifted representations of the baseband in-phase components based on the second coefficient; and

5   an adder operably coupled to add the selected ones of the plurality of shifted representations of the baseband in-phase components to produce the cross coupled in-phase components.

21.   The RFIC of claim 17, wherein the orthogonal-normalizing module comprises:

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a first multiplier module operably coupled to multiply the baseband in-phase components with the second coefficient to produce cross coupled in-phase components;

a subtraction module operably coupled to subtract the cross coupled in-phase components

15   from the baseband quadrature components to produce phase adjusted quadrature components; and

a second multiplier module operably coupled to multiply the phase adjusted quadrature components with the first coefficient to produce the normalized quadrature components,

20   wherein the baseband in-phase components are passed as the normalized in-phase components.

22.   The RFIC of claim 17, wherein the orthogonal-normalizing module comprises:

25   a first programmable register for storing the first coefficient; and

a second programmable register for storing the second coefficient, wherein the first and second coefficients are determined by a trail and error manufacturing test of the gain imbalance and the phase imbalance.

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23.   The RFIC of claim 17, wherein the orthogonal-normalizing module comprises:

a full matrix multiply module operably coupled to multiply the baseband in-phase components and the baseband quadrature components with a coefficient matrix that includes the first and second coefficients to produce the normalized in-phase components

5   and the normalized quadrature components.

24.   The RFIC of claim 17, wherein the orthogonal-normalizing module further functions to:

10   measure local oscillation leakage power to produce a first power measurement;

provide a first magnitude signal to an in-phase portion of the transmitter section and a zero magnitude signal to a quadrature portion of the transmitter section;

15   measure power of the in-phase portion and power of the quadrature portion while processing the first magnitude signal and the zero magnitude signal, respectively, to produce a second power measurement;

provide the first magnitude signal to the quadrature portion of the transmitter section and

20   the zero magnitude signal to the in-phase portion of the transmitter section;

measure the power of the in-phase portion and the power of the quadrature portion while processing the zero magnitude signal and the first magnitude signal, respectively, to produce a third power measurement;

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determine the gain imbalance based on the first, second, and third power measurements;

provide a second magnitude signal to the in-phase portion and to the quadrature portion;

30   measure the power of the in-phase and quadrature portions while processing the second magnitude signal to produce a fourth power measurement;

provide the second magnitude signal to the in-phase portion and a negative second magnitude signal to the quadrature portion;

5   measure the power of the in-phase portion and the power of the quadrature portion while processing the second magnitude signal and the negative second magnitude signal, respectively, to produce a fifth power measurement; and

determine the phase imbalance based on the first, fourth, and fifth power measurements.

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25.   The RFIC of claim 17, wherein the orthogonal-normalizing module normalizes the orthogonal relationship between the baseband in-phase components and the baseband quadrature components by:

15   selecting one of the baseband in-phase components and the baseband quadrature components as a reference component; and

normalizing another one of the baseband in-phase components and the baseband quadrature components to the reference component.

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26.   The RFIC of claim 17, wherein the orthogonal-normalizing module further functions to:

update the first and second coefficients to compensate for at least one of temperature

25   variation and aging.

27.   A method for orthogonal normalization of a radio frequency integrated circuit (RFIC), the method comprises:

determining phase imbalance and gain imbalance of a transmitter section of the RFIC;

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normalizing baseband in-phase components and baseband quadrature components of the transmitter section based on the phase imbalance and the gain imbalance of the transmitter section;

10   coupling the transmitter section to a receiver section of the RFIC in a loop back configuration;

providing a test signal from the transmitter section to the receiver section;

15   determining power of baseband in-phase components, power of baseband quadrature components, and cross-correlation between the baseband in-phase components and the baseband quadrature components of the receiver section while processing the test signal; and

20   normalizing the baseband in-phase components and the baseband quadrature components of the receiver section based on the power of the baseband in-phase components, the power of the baseband quadrature components, and the cross-correlation between the baseband in-phase components and the baseband quadrature components.

25   28.   The method of claim 27, wherein the normalizing the baseband in-phase components of the receiver section comprises:

multiplying the baseband in-phase components with the first coefficient to produce the normalized in-phase components;

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multiplying the baseband in-phase components with the second coefficient to produce the cross-correlation; and

subtracting the cross-correlation from the baseband quadrature components to produce
5   the normalized quadrature components.

29.   The method of claim 27, wherein the determining phase imbalance and gain imbalance of a transmitter section comprises:

10   measuring local oscillation leakage power to produce a first power measurement;

providing a first magnitude signal to an in-phase portion of the transmitter section and a zero magnitude signal to a quadrature portion of the transmitter section;

15   measuring power of the in-phase portion and power of the quadrature portion while processing the first magnitude signal and the zero magnitude signal, respectively, to produce a second power measurement;

providing the first magnitude signal to the quadrature portion of the transmitter section
20   and the zero magnitude signal to the in-phase portion of the transmitter section;

measuring the power of the in-phase portion and the power of the quadrature portion while processing the zero magnitude signal and the first magnitude signal, respectively, to produce a third power measurement;

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determining the gain imbalance based on the first, second, and third power measurements;

providing a second magnitude signal to the in-phase portion and to the quadrature
30   portion;

measuring the power of the in-phase and quadrature portions while processing the second magnitude signal to produce a fourth power measurement;

providing the second magnitude signal to the in-phase portion and a negative second

5   magnitude signal to the quadrature portion;

measuring the power of the in-phase portion and the power of the quadrature portion while processing the second magnitude signal and the negative second magnitude signal, respectively, to produce a fifth power measurement; and

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determining the phase imbalance based on the first, fourth, and fifth power measurements.

30.   The method of claim 27, wherein the determining the power of baseband in-phase

15   components, the power of baseband quadrature components, and the cross-correlation comprises:

measuring in-phase signal level of the receiver section while processing the test signal;

20   measuring quadrature signal level of the receiver section while processing the test signal;

determining the power of the baseband in-phase components based on the in-phase signal level;

25   determining the power of the baseband quadrature components based on the quadrature signal level; and

determining cross-correlation power based on the in-phase signal level and the quadrature signal level.

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31.   The method of claim 27 further comprises:

repeating the normalizing of the transmitter section and the receiver section to fine tune an orthogonal relationship between the baseband in-phase components and baseband quadrature components of the transmitter section and an orthogonal relationship between

5   the baseband in-phase components and baseband quadrature components of the receiver section.

32.   The method of claim 27 further comprises, in an ordered sequence:

10   coupling the transmitter section to the receiver section in the loop back configuration;

providing the test signal from the transmitter section to the receiver section;

determining the power of baseband in-phase components, the power of baseband
15   quadrature components, and the cross-correlation between the baseband in-phase components and the baseband quadrature components of the receiver section while processing the test signal;

normalizing the baseband in-phase components and the baseband quadrature components
20   of the receiver section based on the power of the baseband in-phase components, the power of the baseband quadrature components, and the cross-correlation between the baseband in-phase components and the baseband quadrature components;

determining the phase imbalance and the gain imbalance of the transmitter section;
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normalizing baseband in-phase components and baseband quadrature components of the transmitter section based on the phase imbalance and the gain imbalance of the transmitter section; and

30   repeating the ordered sequence of normalizing of the receiver section and the transmitter section to fine tune an orthogonal relationship between the baseband in-phase

components and baseband quadrature components of the receiver section and an orthogonal relationship between the baseband in-phase components and baseband quadrature components of the transmitter section.

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